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TITLE: MODIFICATION OF THE UPPER ATMOSPHERE WITH CHEMICALS FOUND IN ROCKET EXHAUST

AUTHOR(S): Paul A. Berhardt, John Zinn, Michael Mendillo, and Jeff Baumgardner

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MODIFICATION OF THE UPPER ATMOSPHERE
WITH CHEMICALS FOUND IN ROCKET EXHAUST

Paul A. Bernhardt and John Zinn
Los Alamos National Labortory
Los Alamos, NM 87545

Michael Mendillo and Jeff Baumgardner
Department of Astronomy
Boston University
Boston, MA 02215

ABSTRACT

Rockets, burning above 200 km altitude, release exhaust vapors which react chemically with the plasma comprising the F-region ionosphere. The two major types of atmospheric modification produced by rocket exhaust are: 1) the formation of large scale ionospheric holes, and 2) the enhancement of the airglow emissions. The ionospheric holes are regions tens of kilometers in diameter where the plasma concentration can be reduced by a factor of ten or more. Plasma instabilities may produce irregularities at the edges of the holes. Communication and navigation systems relying on radio propagation through the modified ionosphere may be affected Airglow enhancements are a result of excited neutral species being produced by chemical reactions between the rocket exhaust and the ionospheric plasma. For example, the 630 nm line from atomic oxygen may increase twenty-fold in intensity over the ambient level.

This paper review experimental observations and theoretical treatments of ionospehric modification produced gas releases in the upper atmosphere. Recent experimental measurements of the ionospheric modification by an ATLAS-F launch vehicle will be presented. The plans for future experiments will be discussed.

Introduction

Future, increased activity in space probably requires the firing of rocket engines in the F-region ionosphere. Such engine burns can cause a large scale, temporary reductions in the ionospheric plasma concentration. This paper describes experimental and theoretical studies related to ionospheric depletions produced by rocket exhaust vapors. First, a history of accidental and planned observations of ionospheric "holes" is presented. Second, the theoretical work which has been developed to explain ionospheric modification is outlined. Last, new measurements of ionospheric modifications made during a sequence of ATLAS-F launches is reported.

History

Experimental observations of ionospheric depletions can be classed as either 1) Experiments of Opportunity or 2) Dedicated Experiments (Table 1). The experiments of opportunity involve ground based measurements of F-region disturbances resulting from rocket engine firings above 200 km altitude. The earliest report of such a disturbance was by Booker[1] with the launch of Vangard II. A total of eight such events were reported between 1959 and 1962 (see

Table I). At this time, the ionospheric disturbances were attributed to the displacement of the ambient ionosphere by the rocket exhaust vapors.

Interest in ionospheric modification was re-awakened with the observations reported by Mendillo et al.[2] of a 50% reduction in integrated electron concentration (i.e., electron content) after the launch of Skylab I. This event was remarkable because the effect was observed over a region of 10^6 square kilometers. The currently accepted theory of ionospheric modification involves chemical reactions of the rocket exhaust with the rocket exhaust vapors. The experiments of opportunity in Table I from 1978 to the present have been large campaigns involving large numbers of optical and radio diagnostics.

The dedicated experiments listed in Table I were motivated, in part, by the observations of rocket effects. The small release during the Firefly series of experiments[3] in 1962 was unfortunately too small to be unambiguous. The later Lagopedo, Waterhole, BIME and Spacelab 2 experiments have (or will) yield significant using both *in situ* and ground based diagnostics. For a description of the Lagopedo experiments see (Pongratz et al.[4]). The results of Waterhole I are discussed by Yau et al.[5]. The plans for BIME are presented by Narcisi[6] and for Spacelab 2 are presented by Mendillo and Bernhardt[7].

Table I

Ionospheric Depletion Experiments

Experiments of Opportunity

Designation	Date	Reactive Gases Releases
Vangard II	17 Feb 1959	H_2O, CO_2, OH
Scout (ST-7/P-21)	19 Oct 1961	H_2O, CO_2, OH
Atlas Test No. 1252	2 Oct 1961	H_2O, CO_2, OH
" Test No. 3751	22 Nov 1961	"
" Test No. 3752	2 Dec 1961	"
" Test No. 101	13 Feb 1962	"
" Test No. 122	1 Mar 1962	"
" Test No. 102	13 Aug 1962	"
Skylab I	14 May 1973	H_2O, H_2
Heao-C	20 Sep 1979	H_2O, H_2
Tyros-N	13 Oct 1978	H_2O, CO_2, OH
NOAA-A	27 Jun 1979	"
NOAA-B	29 May 1980	"
NOAA-C	23 Jun 1981	"

Dedicated Experiments

Designation	Date	Material Released	Amount
Firefly-Karen	15 Nov 1962	CO_2	5 kg
Lagopedo I	2 Sep 1977	CO_2, H_2O	88 kg
Lagopedo II	11 Sep 1977	CO_2, H_2O	88 kg
Waterhole I	6 Apr 1980	CO_2, H_2O	88 kg
Waterhole II	Mar 1982	CO_2, H_2O	168 kg
BIME	Sep 1982	CO_2, H_2O	114 kg
Spacelab 2	Nov 1985	CO_2, H_2O, H_2	~4000 kg

Theory

Complete simulation of the response of the upper atmosphere to the release of chemically reactive vapors requires a model which incorporates (1) Neutral Gas Expansion including the effects of condensation collisional heating, diffusion in a reactive nonuniform environment, and transport via winds; (2) Plasma Dynamics including interhemispherical flow along magnetic field lines and transport due to electric fields and winds; (3) Chemical Coupling between the injected neutrals and the ambient plasma atmosphere; (4) Thermal Processes in the Modified Ionosphere describing the changes in ion and electron temperatures; (5) Production of excited species which will radiate Airglow, and (6) Gradient Drift Mechanisms for creation of plasma instabilities.

Condensation

Estimation of the degree of condensation in vapor releases is important for several reasons. First, knowledge of the amount of material which remains in vapor form is necessary to predict the consequences of the release. For example, neutralization of ionospheric plasma involves the chemical reaction of the released gas with O^+ ions in the F-layer. A high degree of condensation reduces the amount of material in vapor form and, consequently, limits the effect on the ionosphere.

Theoretical computations of condensation in rocket exhaust have been conducted by Bernhardt et al.[8]. Table II gives calculated results for the Saturn V J-2 engine, the Space Shuttle main engine and the Space Shuttle Orbital Maneuvering Subsystem (OMS).

The condensation from explosive releases, such as used during Lagopedo and Waterhole, has been estimated to be 10 percent, based on photographic observations[9]. Spectroscopic measurements during Lagopedo I illustrates a broadened enhancement in the optical intensity seconds after the explosive release (Figure 1). This is a result of sunlight scattering off of the water molecule clusters. The individual spectral lines are due to emissions from electronically and vibrationally excited Na, OH and O (Table III).

Diffusive Expansion

The expansion of the injected exhaust is modeled using the three-dimensional simulation described by Bernhardt[10]. Examples of computations for release from a Saturn V are illustrated in Figure 2. The distribution of exhaust vapor in three dimensions and time are computed and stored to be used by ionospheric models.

Table II
Exhaust Condensation

Engine	J-2	SSME	OMS
Exhaust Species	H_2O, H_2	H_2O, H_2	H_2O, H_2, N_2, CO_2, CO
Mass Fraction of H_2O in supply	.952	.964	.236
Nozzle Exit:			
Pressure (Torr)	125.4	294.7	7.76
Temperature (K)	1417	1278	921
Final Mass Fraction of Condensate (kg/kg)	0.243	0.312	0.068
Cluster Radius (10^{-10}m)	9.42	56.4	2.02
Standard Deviation in Cluster Radii (10^{-10}m)	0.4	3.0	0.3
Cluster Temperature (K)	147.25	158.11	100.77

Table III

Lagopedo I Spectra Identification

Chemistry

The generic reactions for plasma neutralization by rocket exhaust are:

Ion-Molecule Reaction

$XY + O^+ \rightarrow XO^+ + Y$ rate: β

Ion-Electron Dissociative Recombination

$XO^+ + e^- \rightarrow X + O^*$ rate: α

Spontaneous Radiation

$O^* \rightarrow O + h\nu$ rate: A

Overall Reaction

$XY + O^+ + e^- \rightarrow X + Y + O + h\nu$

where XY is a reactive molecular species such as H^2O, CO^2, H_2 or OH, and O^* is an electronically excited oxygen atom.

Ionospheric Model

In the F-region ionosphere, the plasma in a particular magnetic flux tube is constrained to remain in that flux tube; consequently, the ionospheric calculations are one dimensional, the dimension being the distance along a magnetic field line. Calculations are made along a sequence of field lines which cross the injected vapor cloud. The computation made on individual field lines are then assembled into a three-dimensional picture. This procedure permits high resolution computation of the ionospheric fluctuations on one field line or in the magnetic meridian containing many field lines or in a 3-D region containing many magnetic meridians. We have conducted experiments which provide data that contains measurements along a single field line or along a simple set of field lines. This greatly simplifies comparison of models with theory.

The ionospheric model has been used to simulate the Lagopedo I experiment. Figure 3 illustrates the electron content measurements made from an instrumented rocket (which flew through the ionospheric hole) to a ground station at Kauai. Also shown in the figures are calculations of the electron content assuming 0% and 50% condensation in the release.

The measurements and calculations for the electron content between the rocket and Kauai show reasonable agreement. The required H_2O condensation seems to be between 0 and 50%. We think that discrepancies are due to uncertainties in the geometry of the experiment and uncertainties in the physical state of the atmosphere.

Recent research in ionospheric modelling[11] has considered the effects of vapor releases on ionospheric instabilities near the magnetic equator. The releases may either trigger or damp out the instabilities. If vapors are injected into the bottom side equatorial ionosphere, the vertical plasma gradients will be increased. The instability growth rate increases with steepening of the bottom side ionosphere. This growth rate is also dependent on the recombination chemistry. The injection of exhaust materials in the ionosphere increases the ion-electron recombination, producing a reduction in the instability growth. Also, chemical releases produce a nonlinear reduction in the amplitude of existing plasma irregularities.

Experimental Results

The launch of the TIROS/NOAA series of satellites have provided a unique opportunity to observe directly the effects of rocket exhaust on the F-region. Table IV lists the last four launches of the TIROS series. Each launch employed an ATLAS-F burning from the ground up to 420 km altitude. The composition of the exhaust is given in Table V.

Electron content and optical measurements were made at the locations indicated on Figure 4. Only a sample of the results from NOAA-B and NOAA-C launches are discussed here. The electron content is determined from VHF signals from the ATS-1 geostationary satellite.

Figure 5 shows a comparison of electron content measurements made at two stations (Boron and Lake Hughes). The content time sequence is identical except for a period of two hours following the launch of NOAA-B. A detailed plot of electron content variations after the launch is illustrated in Figures 6 and 7. The effects of the launch were recorded at a wide range of stations in California, Nevada, and Arizona. The ionospheric depletion rapidly forms and stays until the morning sunrise.

The electron content measurements during the launch of NOAA-C are illustrated in Figure 8. Differences in the rocket trajectory and the ATS-1 satellite account for shift in the location of the maximum reduction in electron content. During the NOAA-C launch, three stations made simultaneous electron content and airglow observations at 630.0 nm wavelength (Figure 9). Current theoretical work is aimed at comparing these two independent types of measurement.

Table IV

NOAA SATELLITE LAUNCHES AND RELATED OBSERVATIONS

		TIME		MEASUREMENTS	
Satellite	Date	UT	(PST)	TEC	Airglow
TIROS-N	10/13/78	11:23	3:23	1	0
NOAA-A	6/27/79	15:52:25	[illegible]:52:25	1	0
NOAA-B	5/29/80	10:53	[illegible]:53	9	1
NOAA-C	6/23/81	10:53	[illegible]:53	5	6

Table V
ATLAS-F EXHAUST PRODUCTS

Species	Deposition Rate (Molecules/sec)	O^+ Reaction Rate (cm^3/sec)	Excited Species
H	1.09×10^{26}	6.8×10^{-10}	---
O	0.27×10^{26}	---	---
OH	$1.5[illegible] \times 10^{26}$	3.0×10^{-10}	$O(^1D)$, $O(^1S)$
H_2O	10.17×10^{26}	2.3×10^{-9}	$O(^2D)$, $O($ S, $OH(^2\Sigma^+)$
CO	11.38×10^{26}	$< 5 \times 10^{-13}$	---
CO_2	4.02×10^{26}	9.5×10^{-10}	$O(^2D)$, $O(^1S)$
O_2	0.30×10^{26}	1.0×10^{-11}	$O(^1D)$, $O(^1S)$

Conclusions

Since 1959, it has been known that the burning of rockets in the ionosphere produces a detectable disturbance in the ionosphere. Recent work has established that ion-molecule chemistry plays a dominant role in the plasma depletion process. Besides reducing the plasma concentration, exhaust releases lead to airglow enhancement and plasma instability quenching.

Experiments of Opportunity and Dedicated Experiments will continue to provide a data base to test theoretical models and to provide estimates of anthropogenic modifications due to rocket engine firings in the upper atmosphere. Such experiments provide a better understanding of the chemical and physical processes taking place in our ionosphere. While the primary purpose of these experiments is to monitor the impact the burning rockets have on the upper atmospheric environment, such experiments also provide information related to planetary atmospheres, plasma instabilities, field-line coupling and airglow emissions.

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